NLO+PS for ttbar+X with aMC@NLO

Rikkert Frederix
University of Zurich

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aMC@NLO

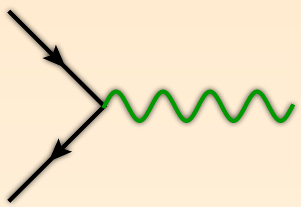
- Automatic version of the "hand-written" MC@NLO
  - Not a library of processes, but a meta code that writes a program to generate events
    - Just like MadGraph, but including NLO corrections
  - Limited only by CPU power
  - Rule of thumb: processes that run quickly on a single computer at LO, run in a reasonable amount of time on a computer cluster at NLO

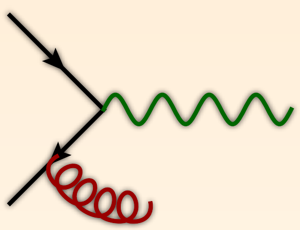
NLOwPS: INGREDIENTS FOR AUTOMATION

- The three ingredients to NLOwPS event generation are
  - Virtual amplitudes: compute the loops automatically in a reasonable amount of time
  - How to deal with infra-red divergences and phase-space integration in an efficient way: virtual corrections and real-emission corrections are separately divergent and only their sum is finite (for IR-safe observables) according to the KLN theorem
  - The matching of these processes to a parton shower without double counting
- All three implemented in the automatic `aMC@NLO` package

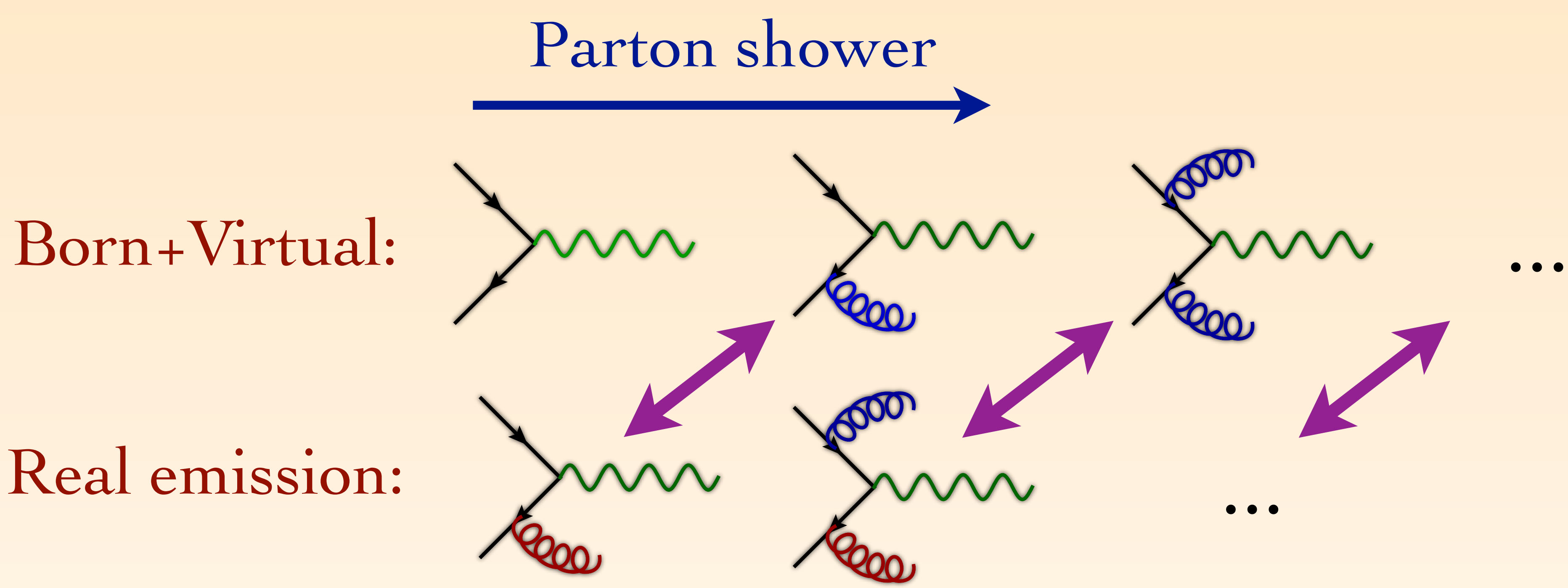
Matching to the Parton Shower

Parton shower

Born+Virtual: 

Real emission: 

Matching to the Parton Shower

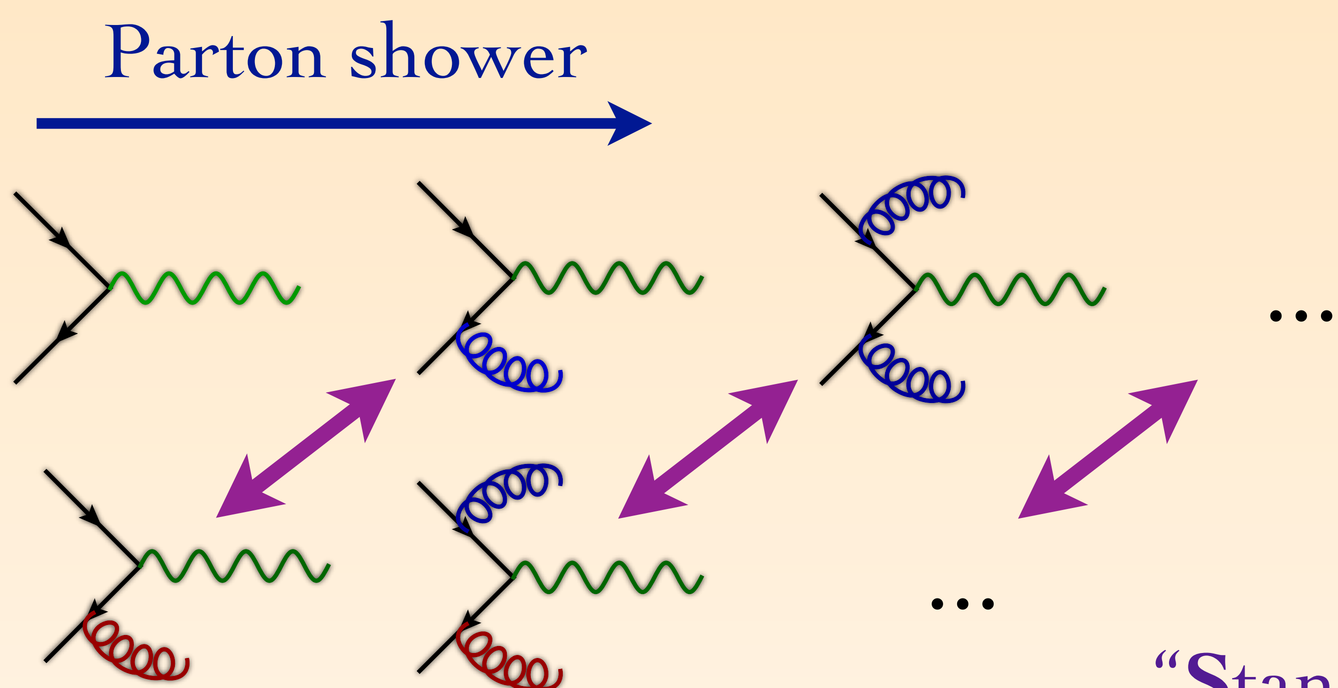


- There is double counting between the real emission matrix elements and the parton shower: the extra radiation can come from the matrix elements or the parton shower
- There is also an overlap between the virtual corrections and the Sudakov suppression in the zero-emission probability

MC@NLO procedure

Born+Virtual:

Real emission:



$$\frac{d\sigma_{\mathrm{MC@NLO}}}{dO} = \left[d\Phi_m\left(B + \int_{\mathrm{loop}} V + \int d\Phi_1 MC\right)\right]\mathcal{F}^{(m)}_{\mathrm{MC}}$$

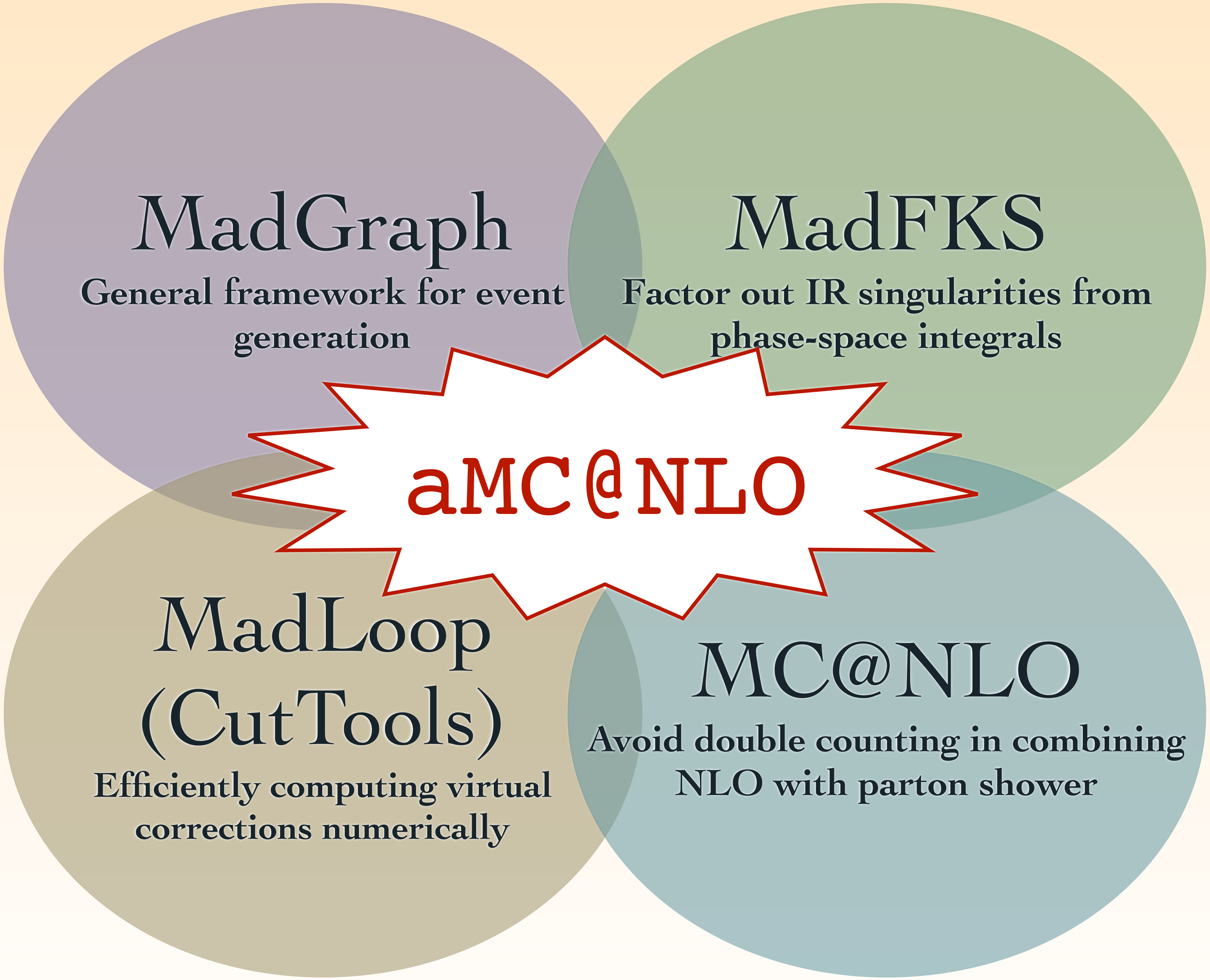
$$+ \left[d\Phi_{m+1}(R - MC)\right]\mathcal{F}^{(m+1)}_{\mathrm{MC}}$$

"Standard **event**"

"Hard **event**"

- Double counting is explicitly removed by including the "Monte Carlo subtraction terms"

The aMC@NLO code



http://amcatnlo.cern.ch

TTBAR + HIGGS

[RF, Frixione, Hirschi, Maltoni, Pittau & Torrielli, arXiv:1104.5613]

- For light Higgs bosons the dominant decay mode is to b quark pairs
- The largest coupling to SM particles is to the top quark
- Simplest tree-level process that combines the two, pp → t tbar H (with H → b bbar), is still very channeling to observe at the LHC
  - Small rates (0.1 (0.7) pb at $\sqrt{s}$ = 7 (14) TeV for a m_H=120 GeV)
  - Large backgrounds from top pair production + (b) jets
- Precise description of the signals and the backgrounds can give a significant contribution to the success of any given analysis
- Use the aMC@NLO to describe the signal process

Set-up

[*RF, Frixione, Hirschi, Maltoni, Pittau & Torrielli, arXiv:1104.5613*]

- Three scenarios

  I) scalar Higgs H, with m_H = 120 GeV

  II) pseudo-scalar Higgs A, with m_A = 120 GeV

  III) pseudo-scalar Higgs A, with m_A = 40 GeV

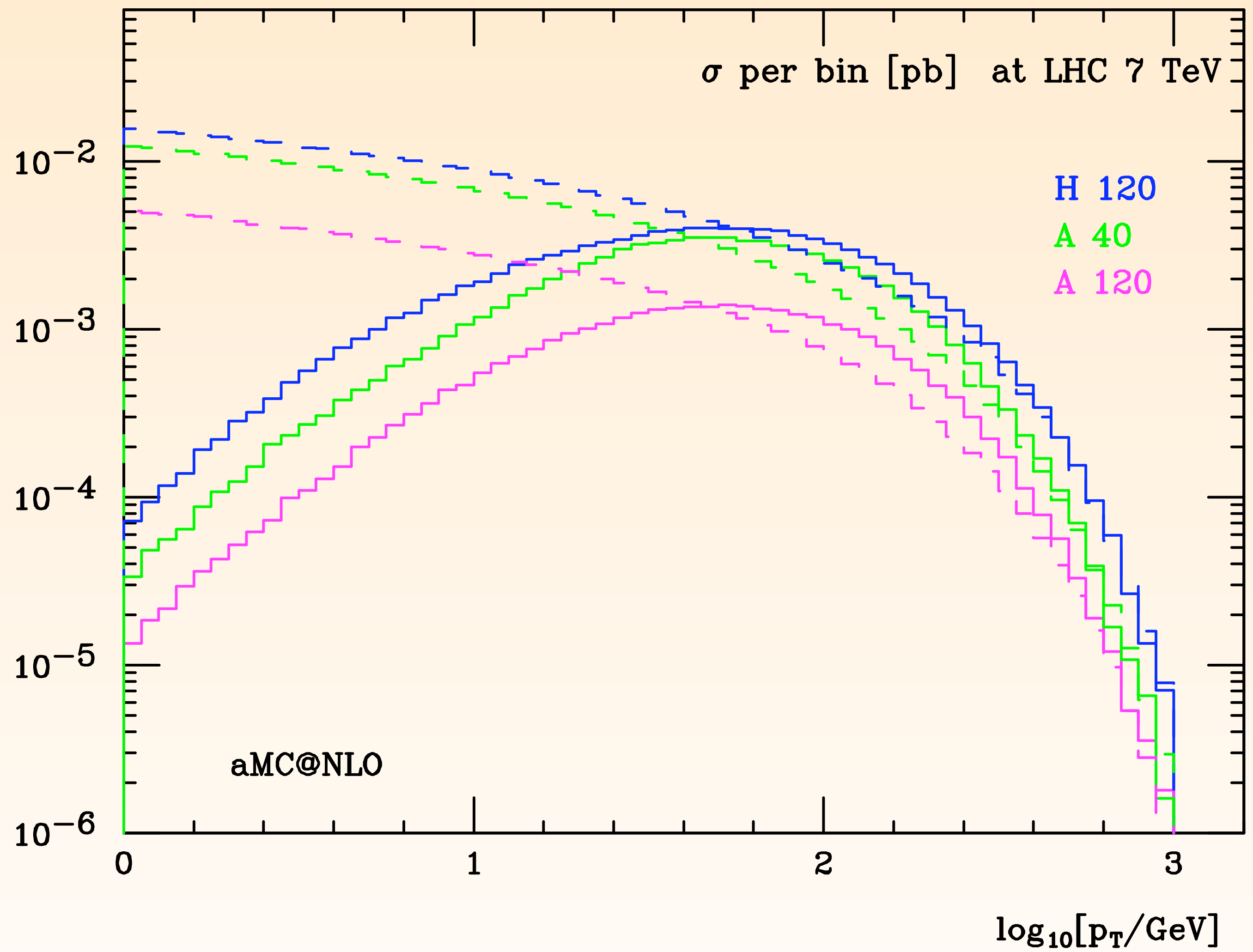
- SM-like Yukawa coupling, $y_t/\sqrt{2}=m_t/v$
- Renormalization and factorization scales $\mu_F = \mu_R = \left(m_T^t m_T^{\bar{t}} m_T^{H/A}\right)^{\frac{1}{3}}$ with $m_T = \sqrt{m^2 + p_T^2}$ and $m_t^{pole} = m_t^{\overline{MS}} = 172.5$ GeV
- Note: first time that pp → ttA has been computed beyond LO

Impact of the shower

[*RF, Frixione, Hirschi, Maltoni, Pittau & Torrielli, arXiv:1104.5613*]

- Three particle transverse momentum, p_T(H/A t tbar), is obviously sensitive to the impact of the parton shower
- Infrared sensitive observable at the pure-NLO level for $p_T \to 0$
- aMC@NLO displays the usual Sudakov suppression
- At large p_T's the two descriptions coincide in shape and rate

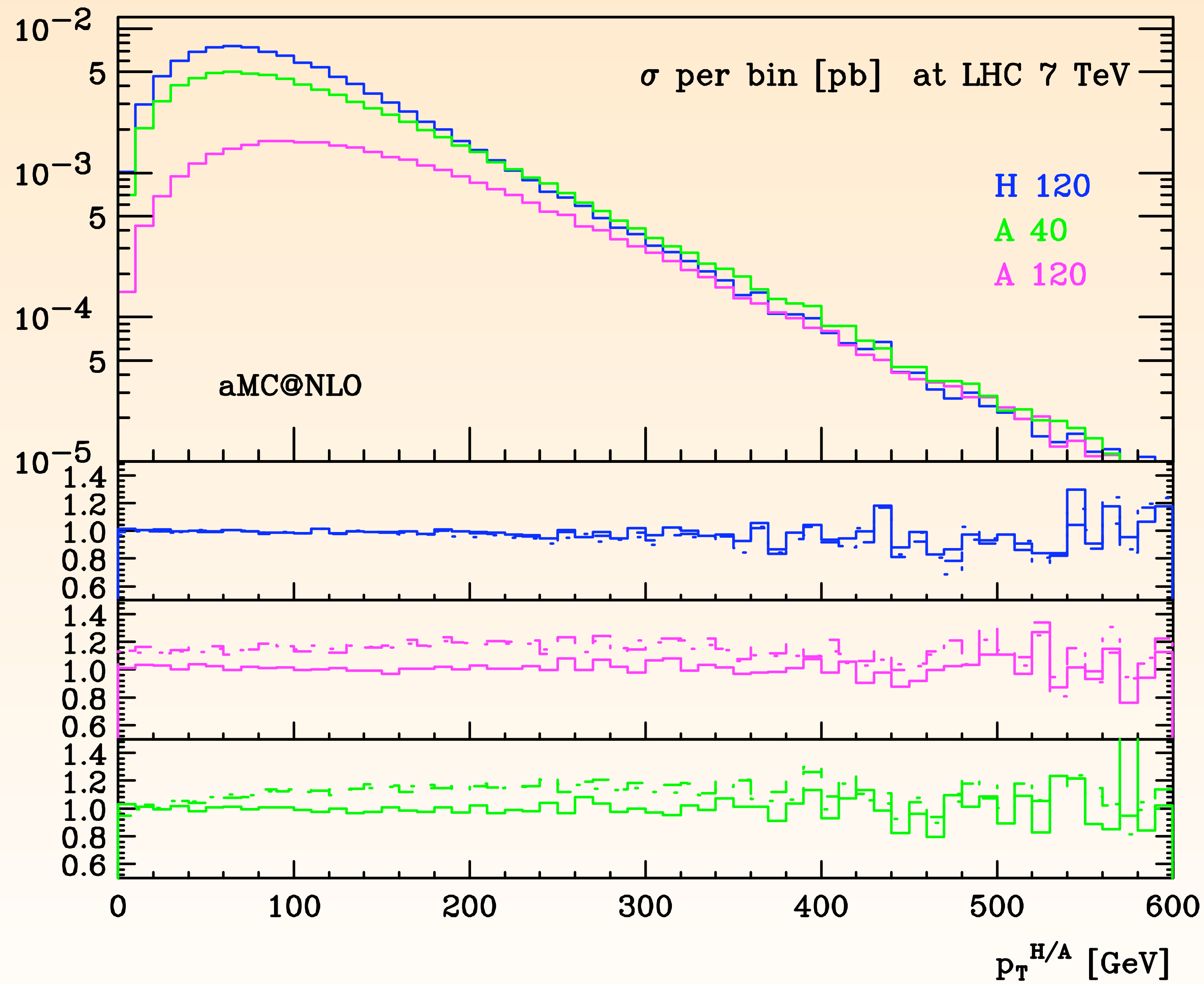
Dashed: NLO, Solid: aMC@NLO



Higgs p_T

[*RF, Frixione, Hirschi, Maltoni, Pittau & Torrielli, arXiv:1104.5613*]

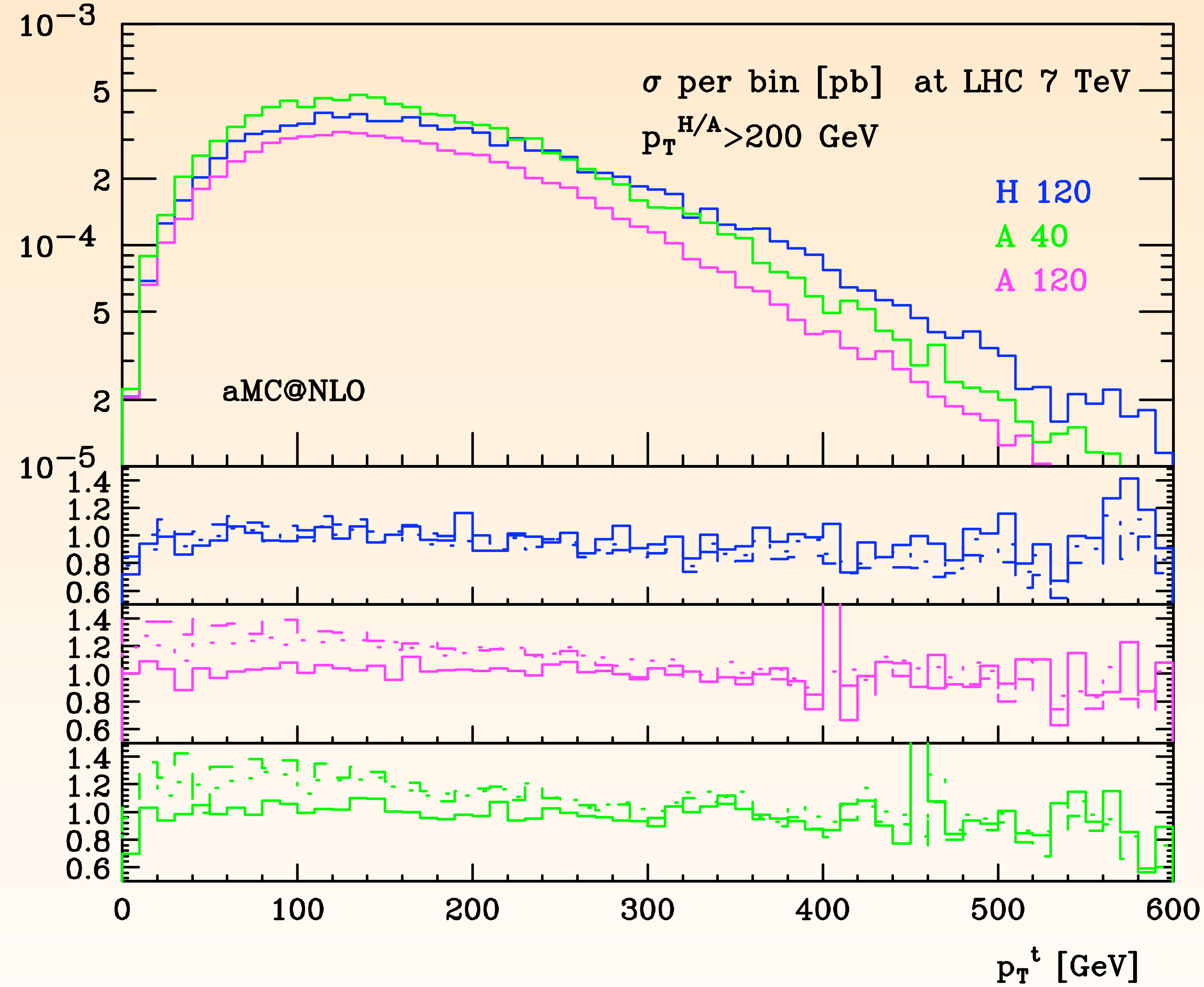
- Transverse momentum of the Higgs boson
- Lower panels show the ratio with LO (dashed), NLO (solid) and LO+PS (dotted)
- Corrections are small and fairly constant
- At large p_T, scalar and pseudo-scalar production coincide: boosted Higgs scenario [*Butterworth et al., Plehn et al.*] should work equally well for pseudo-scalar Higgs



Boosted Higgs

[*RF, Frixione, Hirschi, Maltoni, Pittau & Torrielli, arXiv:1104.5613*]

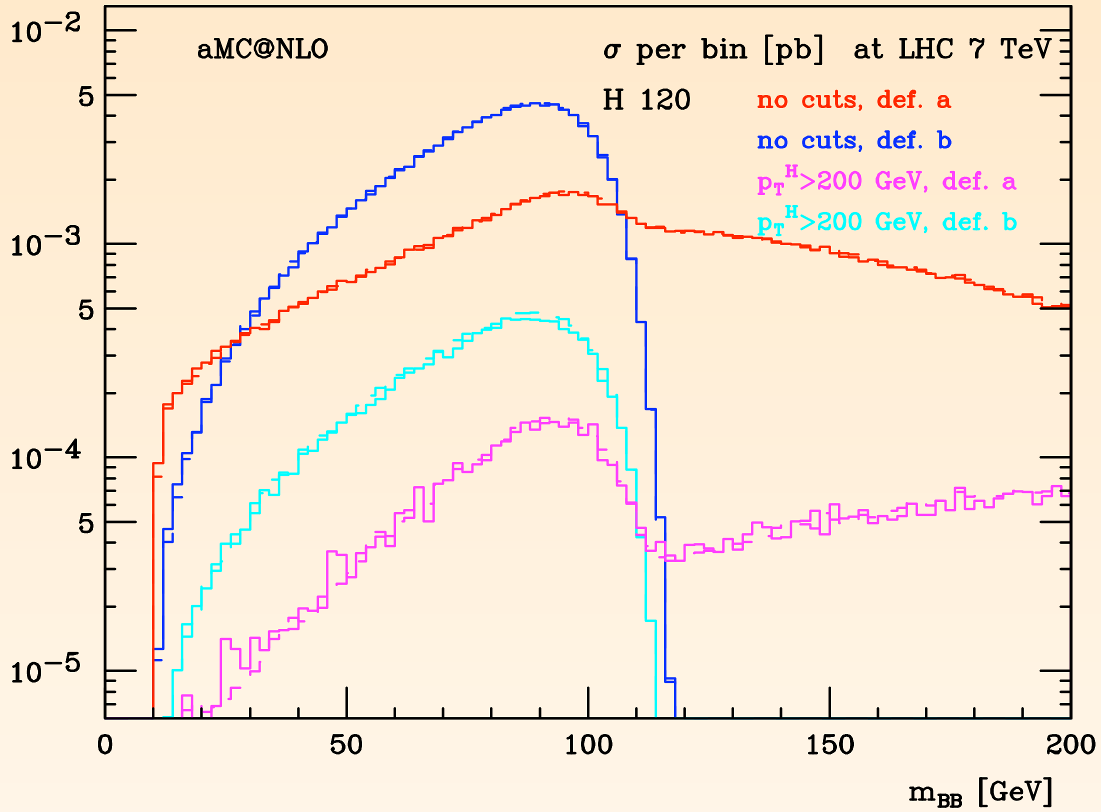
- Boosted Higgs:
  $p_T^{H/A} > 200$ GeV
- Transverse momentum of the top quark
- Lower panels show the ratio with LO (dashed), NLO (solid) and LO+PS (dotted)
- Corrections compared to LO(+PS) are significant and cannot be approximated by a constant K-factor

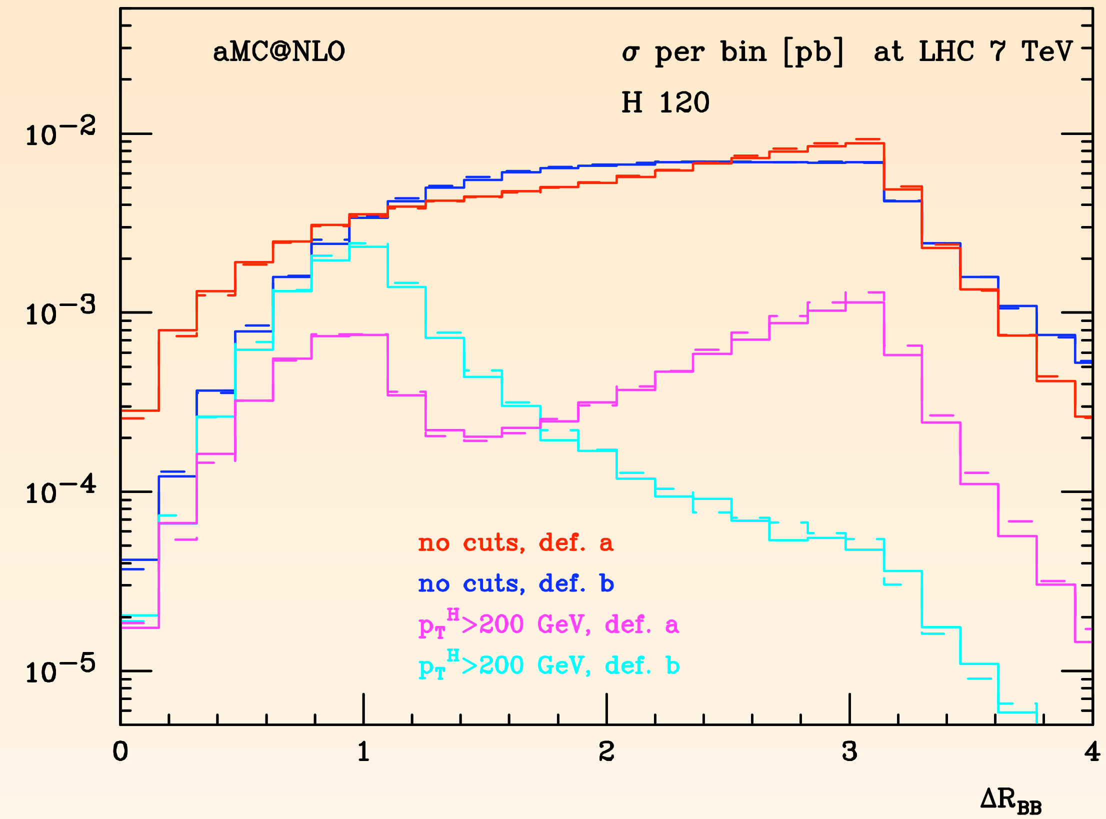


TTH DECAYED

[*RF, Frixione, Hirschi, Maltoni, Pittau & Torrielli, arXiv:1104.5613*]

Dashed: LO+PS, Solid: aMC@NLO

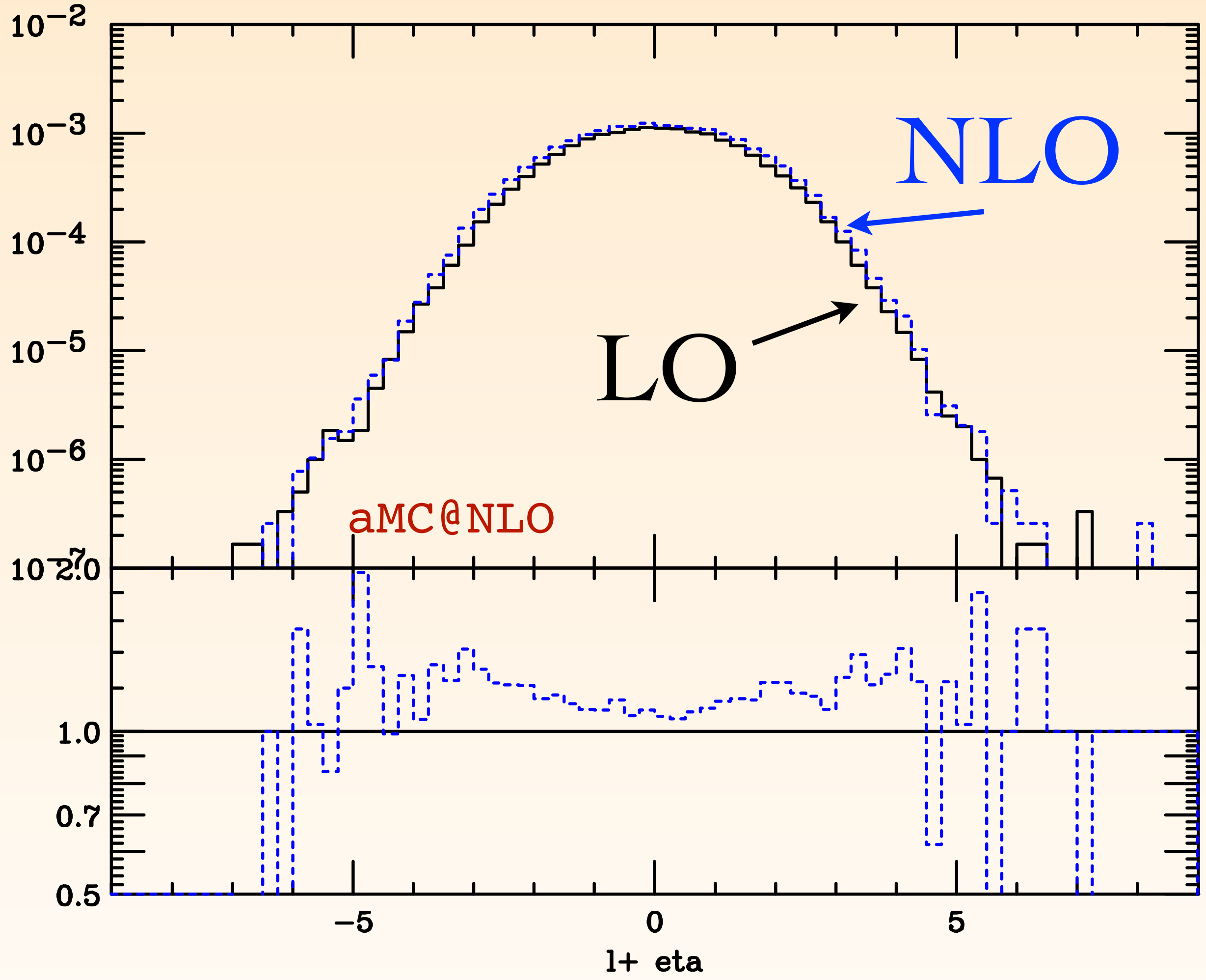




- Two definitions of the B hadron pair in these plots (assuming 100% b-tagging efficiency)
  a) hardest pair in the event
  b) decay products of the Higgs (uses MC truth)
- A cut on the p_T of the Higgs improves the selection of B hadrons from the Higgs decay

TTBAR+W

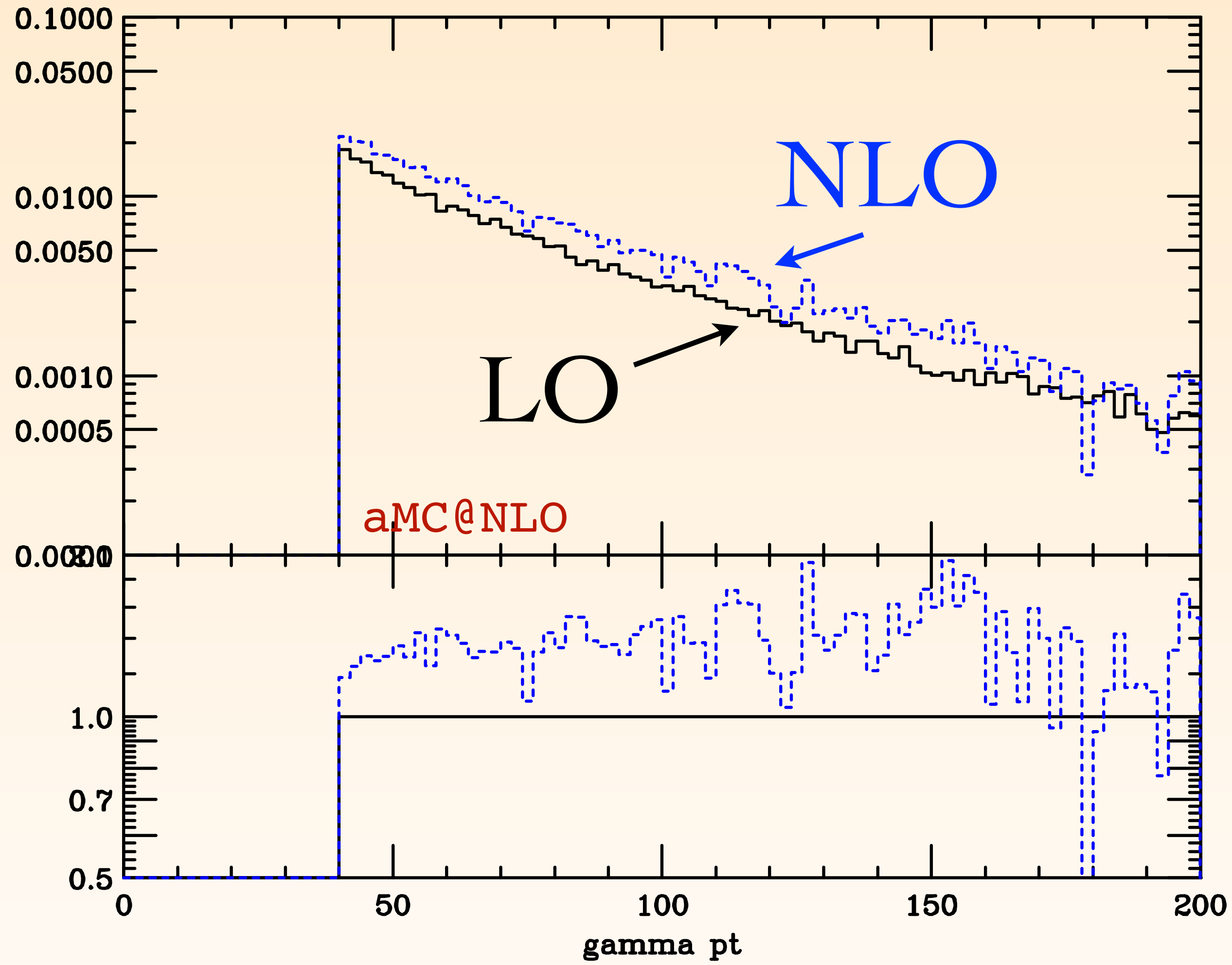
- Sample generated overnight. Plot made this morning



- Rapidity of the charge lepton from the associated W decay

TTBAR+GAMMA

- Sample generated overnight. Plot made this morning



- Transverse momentum of the photon (with some standard Frixione isolation)

aMC@NLO

- That is the power of automation. Code and event generation during the night, phenomenology during the day...

Production + Decay

- What about the decays of the top quarks?
- 0th-level solution: Let the parton shower program do the decays. Lacks spin correlations...
- Simple solution: most important is to include spin correlations between production and decay --> "DecayPackage" (next slides)
- NLO solution: Include NLO corrections in production and decay independently. Non trivial to automate
- Complete solution: generate the full process ("pp -> WWbb") at NLO accuracy
  - Includes decays, spin-correlation, off-shell, resonant and non-resonant effects at NLO accuracy
  - Requires "complex mass scheme" (or something similar) to deal with intermediate resonances
  - Computationally very expensive: only viable when extremely high-precision is a must and/or non-resonant contributions are enhanced due to analysis cuts

DecayPackage

In collaboration with Pierre Artoisenet and Robert Rietkerk

- **Wish list:**
  - For any event sample (with unweighted events -- LO or MC@NLO), include the decay of any of the final state particles
  - Keep all spin correlations between production and decay
  - Generate unweighted events
  - Already available in MC@NLO for ttbar and single top production *[Frixione, Laenen, Motylinski & Webber, hep-ph/0702198]*

DecayPackage

In collaboration with Pierre Artoisenet and Robert Rietkerk

- **How to get this:**
  - Read event
  - Generate decay kinematics
  - Reweight event by the ratio $|M_{\mathrm{Production+decay}}|^2 / |M_{\mathrm{Production}}|^2$
    - or, better, do a (secondary) unweighting against $|M_{\mathrm{Production+decay}}|^2 / |M_{\mathrm{Production}}|^2$:
    - Generate many decay momenta until:

$$\boxed{|M_{\mathrm{Production+decay}}|^2 / |M_{\mathrm{Production}}|^2 > \mathrm{Random\#} \times \mathrm{UpperBound}(|M_{\mathrm{Production+decay}}|^2 / |M_{\mathrm{Production}}|^2)}$$

DecayPackage

In collaboration with Pierre Artoisenet and Robert Rietkerk

- **What we need:**
  - Matrix elements for production and production+decay processes
  - Upper bound on ratio of $|M_{\text{Production+decay}}|^2 / |M_{\text{Production}}|^2$ to be able to unweight the events
  - Generate decay kinematics

DecayPackage

In collaboration with Pierre Artoisenet and Robert Rietkerk

- **Matrix elements:**
  - For each event, read the particles and check if the corresponding matrix elements were already generated
  - If not: generate the tree-level production and production+decay matrix elements using madgraph5
  - Use the "decay chain syntax" for the production+decay matrix elements to only generate diagrams consistent with the decay process

DecayPackage

In collaboration with Pierre Artoisenet and Robert Rietkerk

- **Upper bound on $|M_{\text{Production+decay}}|^2 / |M_{\text{Production}}|^2$:**
  - The upper bound is independent from the production process and kinematics! *[Frixione, Laenen, Motylinski & Webber, hep-ph/0702198]*
  - For the first 5 events in the event file, use several 1000 decay PS points and compute $|M_{\text{Production+decay}}|^2 / |M_{\text{Production}}|^2$ to determine the maximum weight found
    - To be on the safe side, the variation in the maximum weights found in the 5 events is added twice to the maximum weight
  - When looping over all events, use this maximum weight to do the unweighting of the decay kinematics

DecayPackage

In collaboration with Pierre Artoisenet and Robert Rietkerk

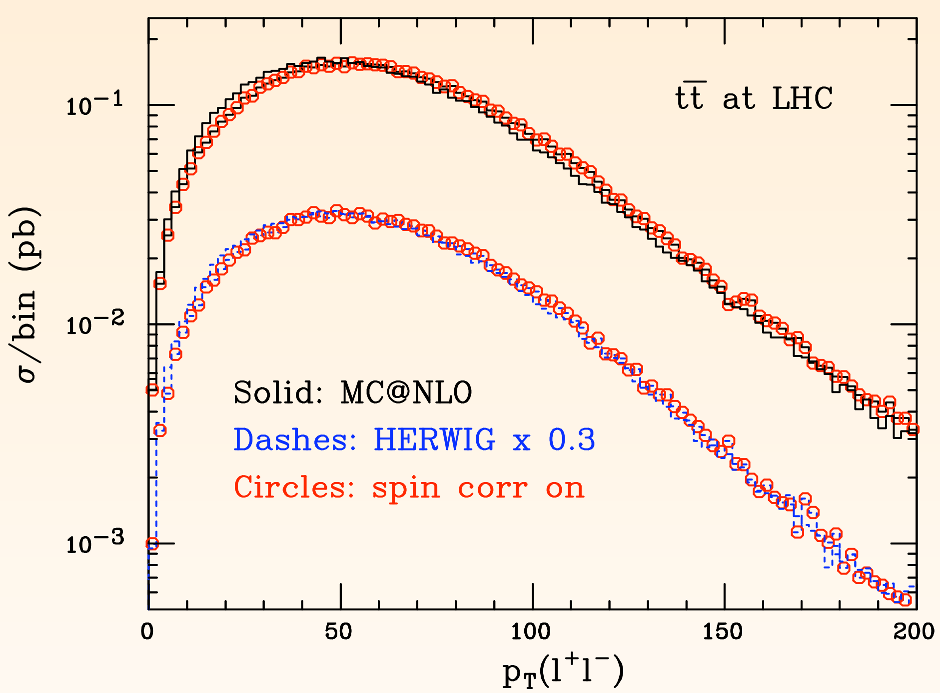
- **Spin correlations in aMC@NLO events:**
  - For most observables, spin correlations have a tiny effect: including them at tree level is enough
    - H-events: use the “real-emission matrix elements” to reweight them
    - S-events: use Born matrix elements to do the reweighting
  - This guarantees NLO accuracy for observables related to the production process (e.g. p_T of the top quark)
  - This includes all spin correlations (apart from the non-factorizable correlations of virtual origin) in the production+decay process

DECAYPACKAGE

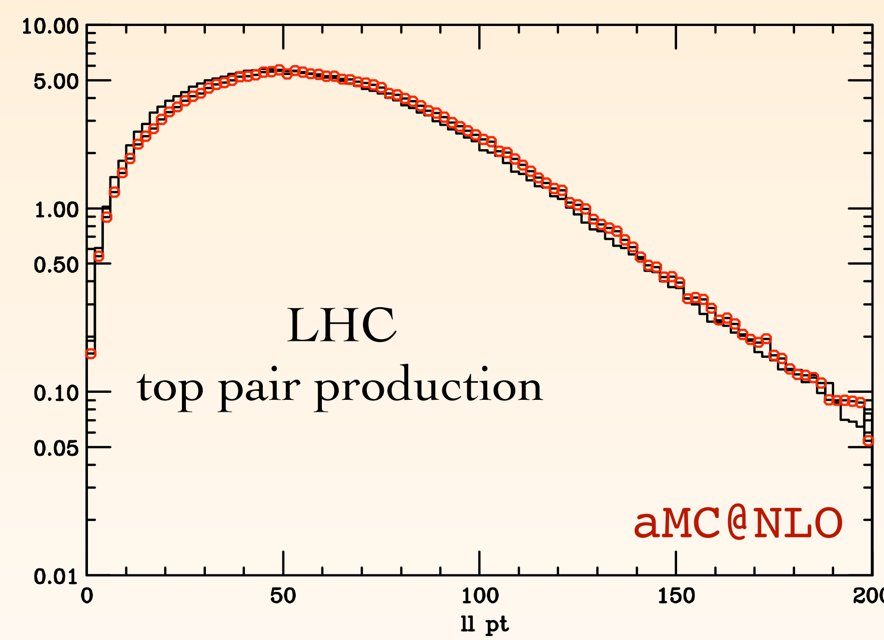
In collaboration with Pierre Artoisenet and Robert Rietkerk

- **Validation plots:**

Frixione, Laenen, Motylinski & Webber, hep-ph/0702198



aMC@NLO+DecayPackage



- Top pair production

DecayPackage

In collaboration with Pierre Artoisenet and Robert Rietkerk

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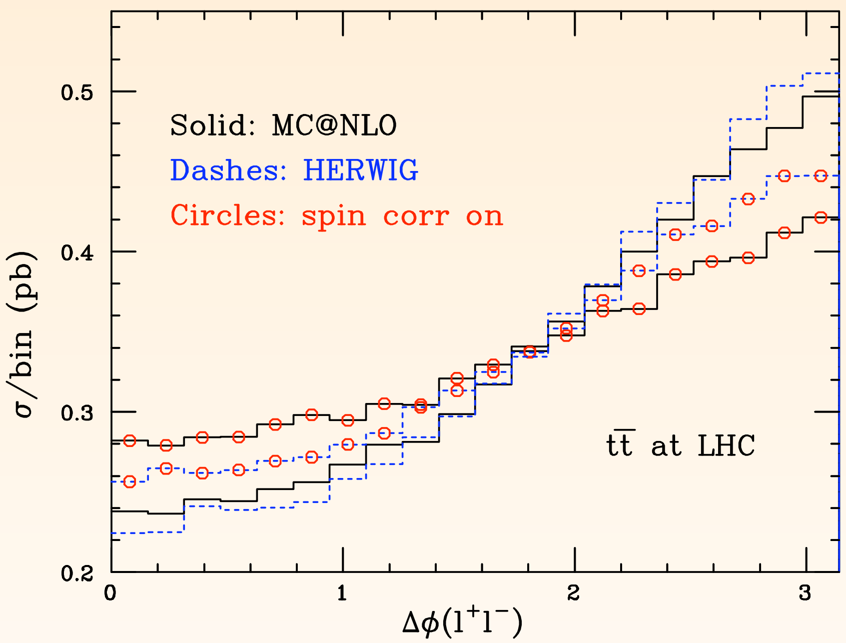

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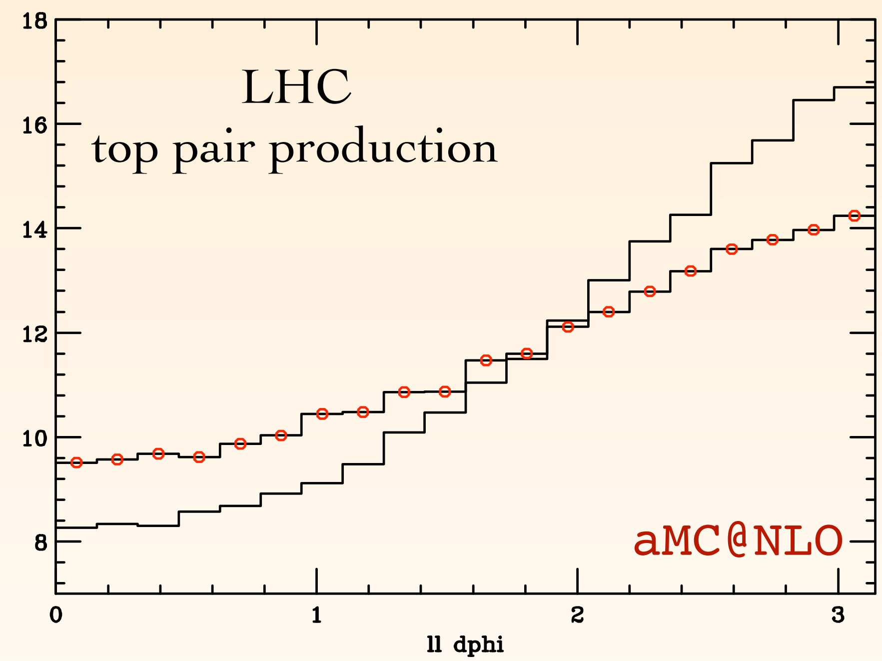

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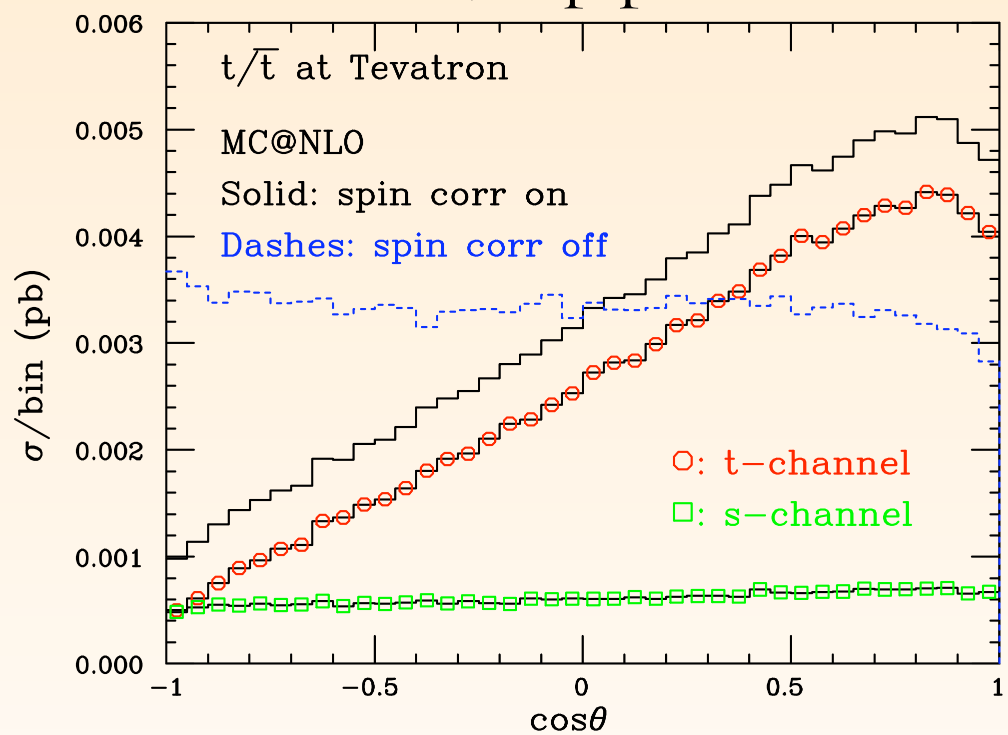
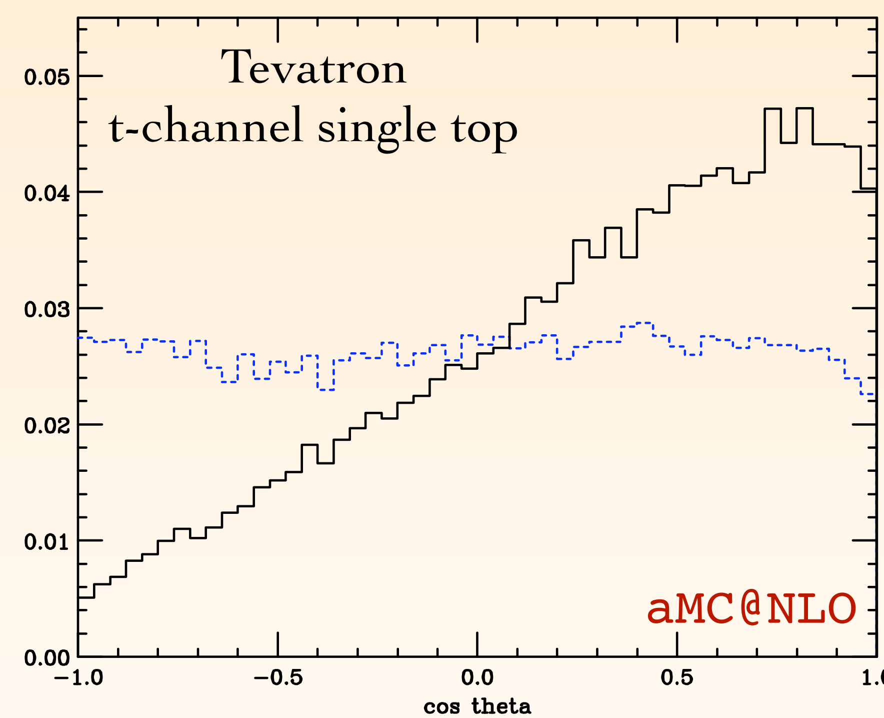


aMC@NLO+DecayPackage

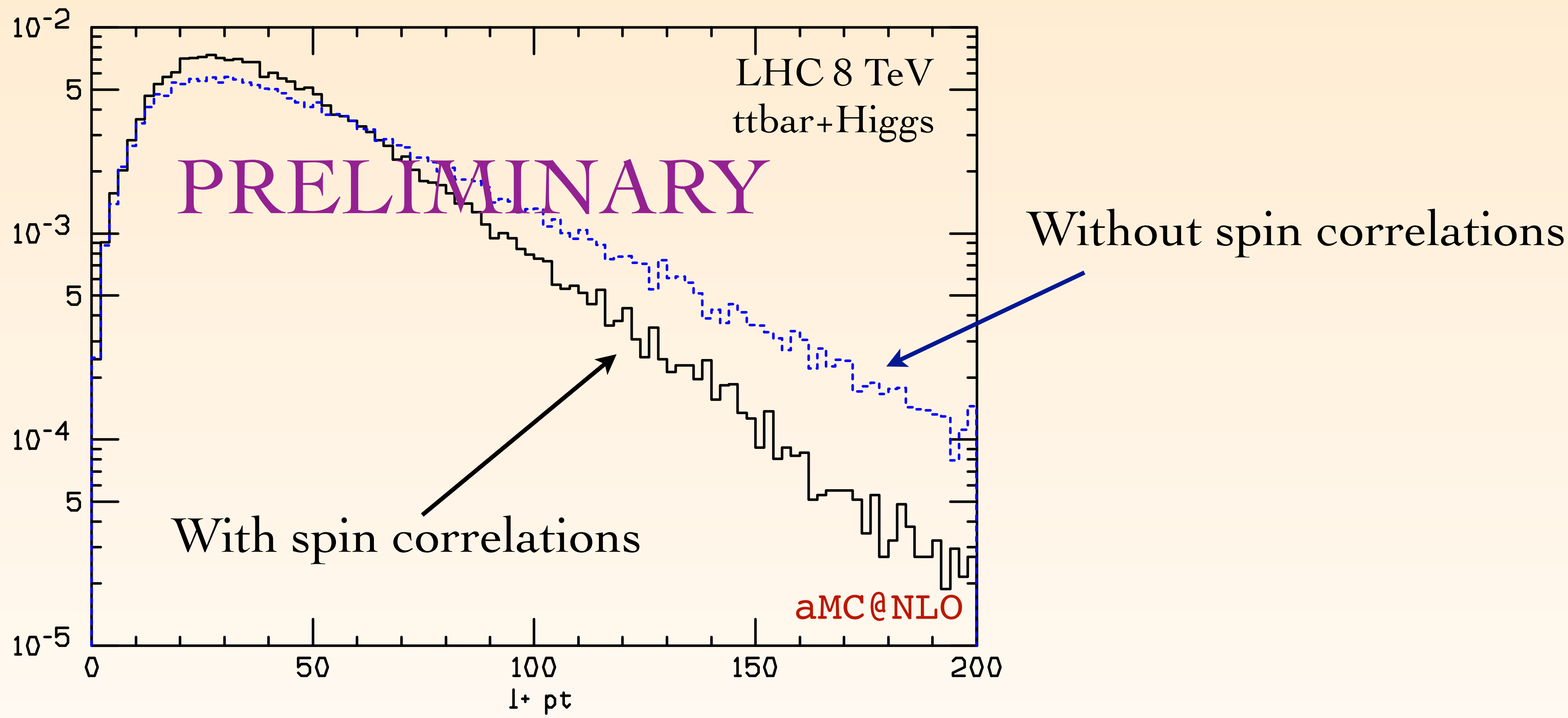


- t-channel single top production

DecayPackage

In collaboration with Pierre Artoisenet and Robert Rietkerk

- **Example ttbar+Higgs:**



- Transverse momentum of positively charged lepton in di-leptonic top decays

DecayPackage

In collaboration with Pierre Artoisenet and Robert Rietkerk

- **Possible improvements:**
  - Better handling of the processes: e.g. if there is an intermediate resonance written in the event file, only generate the matrix elements conform that resonance
  - Speed-up: speed for NLO processes is satisfactory, for LO it slower than the direct integration of the matrix elements including decay
  - Include Breit-Wigner effects: requires "reshuffling" of the production process momenta. PDF effects to be included here?

aMC@NLO for BSM

- Two extra complications:
  - Automatic virtuals: OPP method only gets part the "rational contributions" and no UV-renormalization counterterms. Need special diagrams to complete them. Use FeynRules to generate the corresponding Feynman rules automatically
  - On-shell resonances appearing in the real-emission contributions should be avoided/subtracted. Similar problem of double counting (already removed within MG5) in ME+PS matching *[Alwall, Maltoni, de Visscher]*. Double counting also subtracted in the MadGolem project *[Concalves-Netto, Lopez-Val, Mawatari, Plehn, Wigmore]*

Summary

- aMC@NLO ("automatic MC@NLO") can be used to generate events for any SM process at NLO accuracy (limited only by CPU power)
  - ttbar+Higgs, ttbar+gamma, ttbar+W, ttbar+... are all straight-forward to produce. Time can be spend on studying the phenomenology instead of coding and or performing the calculation
- DecayPackage: efficiently including spin correlations between production and decay of heavy particles
- Code is currently being rewritten in the madgraph5 framework and will become available this year
- Website: http://amcatnlo.cern.ch